Method of State Estimation and Identification of the Arial Vehicle under Destabilizing Action of Weather Conditions

V.M. Kazak
National Aviation University
Kiev, Ukraine
profkazak@ukr.net

D.O. Shevchuk
National Aviation University
Kiev, Ukraine
dmitroshevchuk@gmail.com

N.A. Tymoshenko
National Aviation University
Kiev, Ukraine
T_Nataly @ukr.net

I.V. Prochorenko
National Aviation University
Kiev, Ukraine
proshorenko_i@mail.ru

Abstract—Here we explain method and models for hover mode of aerial vehicle (helicopter) as well as measurements of parameters of this flight mode that requires smaller volume of calculation and preserves high speed and accuracy of stabilization. Also we investigate reduction of number of state vectors and volume of calculation via usage of extended Kalman filter and standard sensors.

Keywords—control; control system; helicopter; filter; perturbation; stabilization

I. INTRODUCTION

Due to increased use of helicopters to perform work on the point objects: discharge of cargos into pipes holes (for example, nuclear power stations), the establishment of television and radio towers sections and their antennas, rescue, landing on a limited area etc, there is a need stabilization of the helicopter with precision accuracy in the mode of hovering over a point object in terms of the negative impact of environmental factors (Fig. 1) [1] – [3].
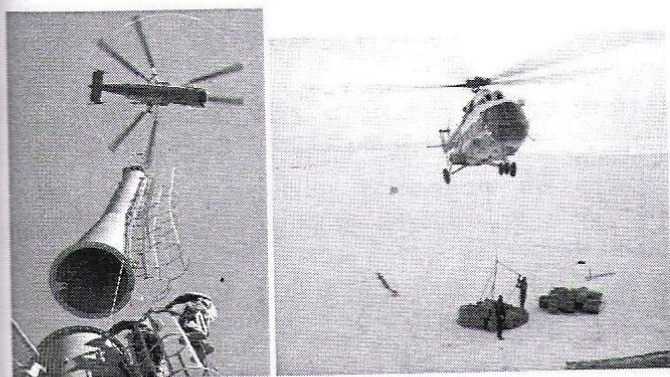

Fig. 1.   Example of precision stabilization of the helicopter.

It's difficult for the crew to solve that issue. First reason is fast change of conditions in the system "helicopter-point object- weather". Second reason is slow reaction of the system "helicopter-point object- weather" comparing with speed of perturbations. That's why it necessary to create stabilizer as part of ACS with high speed of reaction and precision accuracy. Classic theory of control used for mentioned issue can't provide necessary accuracy and speed-of-response. LOG theory is the most popular now. Information we need for LOG theory stabilization implementation we can get in two ways:

- usage of additional sensors and real improvement of their accuracy. That way is not reasonable because of weight, seizes and cost of equipment increase;

- usage of standard navigation equipment and improved program product. Second way choosed for that work.

II. PROBLEM STATEMENT

For construction of stabilizer of precision accuracy of helicopter's hovering as part of ACS we need to develop the model of stabilization of system "helicopter-point object-weather" and also the model of measurement of parameters of helicopter hovering above point objects.

III. REVIEW

Significant gains achieved domestic and foreign scientists in the field of automation control moving objects for different purposes. Fundamental scientific results are presented in the works of Academician NAS of Ukraine Kuntsevych V.M., Hostyev V.I., Kazak V.N., Zbrutsky A.V., Tunic A.A., Larina V.B., Kulik A., Tkachenko O.M., Lozinski A .O., Filaretov V.F. (Russia), Tod M. (Japan), Hover F.S., Linklater A. (USA) and others.

But theoretical studies in stabilizing the helicopter in hovering mode, designed for working on point objects currently not implemented in full. Therefore there is a need for a stabilizer as part of the automatic control system (ACS), which would have high reaction speed and precision accuracy stabilization. Classical methods of control of aircraft for this task does not meet the requirements for accuracy and speed, and requires additional information sensors.

IV. PROBLEM SOLUTION

The aggressive action of weather conditions on the helicopter in flight, and especially in hovering mode, causes a breach of stabilization in relation to the trajectory and that is the most important reason of organization of precision stabilization in relation to the center of the given point object. (Fig. 2, point O). Random character of input influences: internal and external perturbation actions that affect helicopter in hovering mode, requires realization of the management strategy based on probabilistic characteristics of the measured parameters [4]:

$$z(t_k) = z[x(t_k), u(t_k), g(t_k), \varphi(t_k), k],$$

where $z(t_k)$ is the vector of measured reactions; $x(t_k)$ are variables of the state; $u(t_k)$ is the variable input of managing actions; $g(t_k), \varphi(t_k)$ is the measurable and not measurable internal and external perturbations respectively. That is, to determine the appropriate managing action $u_r(t_k)$, that would ensure the execution of the conditions of tracking in the steady mode of the real $X_r(t_k)$ parameter values of helicopter's hovering accordingly to predetermined parameter $X_p(t_k)$ [5]:

$$\lim_{t \to \infty} X_r(t_k) = \lim_{t \to \infty} X_p(t_k). \tag{1}$$
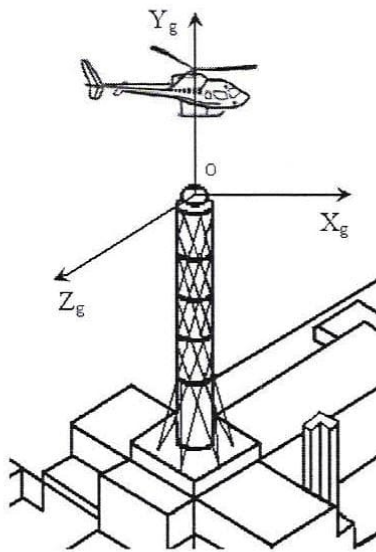

Fig. 2. Stabilization of helicopter's hovering over a point object.

The task of state estimation and identification is as follows: for the helicopter, given by an appropriate mathematical model, to determine control

$$u(t_k) = f(x(t_k), g(t_k), \varphi(t_k), V, t).$$

Method of state estimation and identification of the arial vehicle under destabilizing action of weather conditions is as follows: first of all we need to evaluate the quality of stabilization on the value of deviation of mathematical expectation $\varepsilon_M(t_k)$ and variance $\varepsilon_D(t_k)$. Further it's necessary to work out "helicopter-point object" system model condition evaluation.

Control process and in flight helicopter stabilization quality is determined by the error that is caused by the mismatch $r(t_k)$ between given $x_p(t_k)$ and current $x_r(t_k)$ values of the controlled/stabilized value:

$$r(t_{k+1}) = x_p(t_k) - x_r(t_{k+1}). \tag{2}$$

Under the influence of perturbations stabilization parameters would deteriorate and discrepancies (2) would not have zero value and the helicopter would hand off the point (Fig. 2)

$$r(t_{k+1}) = x_p(t_k) - x_r(t_{k+1}) \neq 0. \tag{3}$$

Requirements violation monitoring process (1) can be formalized as following:

$$\overline{x}(t_{k+1}) = A\hat{x}(t_k) + Bu(t_k), \tag{4}$$

$$\hat{x}(t_{k+1}) = \overline{x}(t_{k+1}) - Kr(t_{k+1}), \tag{5}$$

$$r(t_{k+1}) = z(t_{k+1}) - C\overline{x}(t_{k+1}),, \tag{6}$$

where $\overline{x}(t_{k+1})$ is the estimated evaluation $x(t_{k+1})$ before measuring at time t_{k+1}; $\hat{x}(t_{k+1})$ is the evaluation of "helicopter-ACS-point object" system state parameters, that includes measurement at time t_{k+1}; $r(t_{k+1})$ is the discrepancy; K is the matrix of Kalman coefficients filter.

"Helicopter-ACS-point object" system reaction error on perturbations has also random nature and is defined as the difference between the system state at time t_k and its change at time t_{k+1}

$$\overline{\xi}(t_k) = x(t_k) - \overline{x}(t_k), \tag{7}$$

$$\hat{\xi}(t_k) = x(t_k) - \hat{x}(t_k). \tag{8}$$

After substracting from the equation (4) of system state of another equation that includes external factors and internal processes destabilizing action

$$x(t_{k+1}) = Ax(t_k) + Bu(t_k) + B\Delta u(t_k), \tag{9}$$

we obtain:

$$\overline{\xi}(t_{k+1}) = A\xi(t_k) + B\Delta u(t_k). \tag{10}$$

After combining measurements equations:

$$z(t_k) = Cx(t_k), \tag{11}$$

with equations (5), (6), (7) we obtain:

$$\hat{x}(t_{k+1}) = \overline{x}(t_{k+1}) + KC\overline{\xi}(t_{k+1}). \tag{12}$$

Us represent the equation (12) in the form of an error

$$\hat{\xi}(t_{k+1}) = \overline{\xi}(t_{k+1}) - KC\overline{\xi}(t_{k+1}). \tag{13}$$

Given that "helicopter-ACS-point object" measurement of reaction of system error (13) is random and has normal law of

errors, it can be characterized by expected squared error. Such system optimality condition can be defined as follows [6]:

$$\eta\left[\hat{\xi}(t_{k+1})\right] = M\left[r^2(t_{k+1})\right] = \min, , \qquad (14)$$

and for hovering mode

$$\eta\left[\hat{\xi}(t_{k+1})\right] = M\left[r^2(t_{k+1})\right] = 0. \qquad (15)$$

The value of $\eta\left[\hat{\xi}(t_{k+1})\right]$, as the initial covariance of "helicopter-ACS-point object" system error of $\hat{\xi}(t_{k+1})$ (Fig. 2) can be defined through the expected error and error variance. Generalized criterion (14) is mathematical expectation and error variance (13) given function extremum criterion:

$$f\left[M(\hat{\xi}(t_{k+1})), D(\hat{\xi}(t_{k+1}))\right] = \text{extremum}. \qquad (16)$$

If helicopter deviation from point O (Fig.2) in hovering mode is considered as an error, then stabilization system task is to ensure the minimum of the function (16), i.e.

$$f\left[M(\hat{\xi}(t_{k+1})), D(\hat{\xi}(t_{k+1}))\right] = 0. \qquad (17)$$

Requirements (17) represent the offset of the adjustable parameter under mathematical expectation

$$\varepsilon_M(t_k) = M_p(t_{k+1}) - M_r(t_{k+1}) \to 0, \qquad (18)$$

and variance

$$\varepsilon_D(t_k) = D_p(t_{k+1}) - D_r(t_{k+1}) \to 0, \qquad (19)$$

that are recorded with consideration (13) and shall tend to the minimum allowable values, for our task it is zero.

If there is a possibility to evaluate the quality of stabilization on the value of deviation of mathematical expectation $\varepsilon_M(t_k)$ and variance $\varepsilon_D(t_k)$, that provide reaching given quality parameters of the stabilization process, we shall minimize the corresponding functionality [7]:

$$J_\varepsilon = \frac{1}{N}\sum_{i=1}^{N}\left(\varepsilon_M^2 + \varepsilon_D\right) \to 0. \qquad (20)$$

Quality criterion (20) gives an opportunity to carry out structural synthesis of stabilization and control system, with which you can implement automatic stabilization of the helicopter, including hovering mode, in casual weather conditions. Let's define the task of the structural synthesis of automatic control system (ACS) as follows: for the helicopter, given by an appropriate mathematical model, to determine control

$$u(t_k) = f\left(x(t_k), g(t_k), \varphi(t_k), V, t\right), \qquad (21)$$

as a function of specified arguments that provides condition (20) performance. In function (21) V is the measuring devices error.

Control actions (21) are formed by two parallel channels (Fig. 3), one of which is a quick-action based on the accelerations vector $\bar{J}$, and the second – inertia channel based on the speed vector $\bar{V}$. Moreover, the signal of the inertia channel is subtracted from the quick-action channel signal.
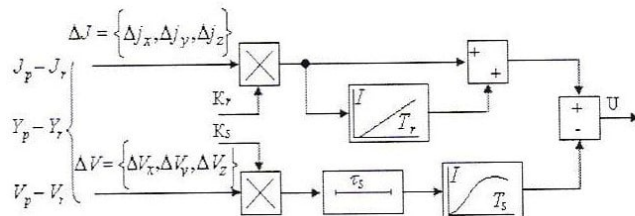

Fig. 3.   Block diagram of control actions formation.

The developed stabilizer (Fig. 3), which is a part of ACS, solves the problem of simultaneous performance and storage stability of the automatic control system that is impossible to implement in standard schemes, where there is a contradiction, namely the growth of amplification coefficient, causes a decrease in supply stability of system of automatic stabilization and control.

Acceleration sensors j_x, j_y, j_z, that characterize short-circuit fluctuations of helicopter mass center, are first to react on the violations of conditions (20). The second are helicopter mass center O point displacement speed measuring devices (see Fig. 2) $\dot{H}, \dot{X}, \dot{Z}$, which characterize long-circuit of helicopter mass centre fluctuations. Therefore, to solve the task of helicopter on given point object O (see Fig. 2) point hovering stabilization, you need to make a model of the system with zero accelerations relative to the centre of point object. It should be noted, that in case of non-using of such model the system (9) state vector, and therefore a vector of measurements (11), taking into account that accelerations vector is the first derivative of the speed and the second from the distance, are significantly reduced (up to 6 parameters). In view of this the differential equation of "helicopter-point object" system takes the form [8]:

$$\begin{aligned}
&\Delta\dot{S}(t_k) = \Delta V(t_k), \ \Delta S = \left\{\Delta X, \Delta Y, \Delta Z\right\}, \\
&\Delta V = \left\{\Delta V_x, \Delta V_y, \Delta V_z\right\}, \\
&\Delta\dot{V}(t_k) = -J_h(t_k) + \dot{W}_h, \ J_h = \left\{j_x, j_y, j_z\right\}, \\
&\dot{W}_h = \left\{\dot{W}_x, \dot{W}_y, \dot{W}_z\right\},
\end{aligned} \qquad (22)$$

where $J_h = \left\{j_x, j_y, j_z\right\}$ is the accelerations vector, $\dot{W}_h = \left\{\dot{W}_x, \dot{W}_y, \dot{W}_z\right\}$ is the perturbation accelerations vector.

Therefore, "helicopter-point object" system model condition evaluation using extended Kalman EKF filter acquires following composition:

$$
\begin{bmatrix} \Delta\dot{S}(t_k) \\ ---- \\ \Delta\dot{V}(t_k) \end{bmatrix}_{6\times1} = \begin{bmatrix} 0 & | & I \\ - & - & - \\ 0 & | & 0 \end{bmatrix}_{6\times6} \begin{bmatrix} \Delta S(t_k) \\ ---- \\ \Delta V(t_k) \end{bmatrix}_{6\times1}
$$
$$
+ \begin{bmatrix} 0 & | & 0 \\ - & - & - \\ 0 & | & I \end{bmatrix}_{6\times6} \begin{bmatrix} 0 \\ ---- \\ -J_h(t_k) \end{bmatrix}_{6\times1} + \begin{bmatrix} 0 \\ ---- \\ W_h(t_k) \end{bmatrix}_{6\times1} .
\tag{23}
$$

If "helicopter-point object" system model is given by the relation type (22), then you can make the state transition matrix for it as follows [5]:

$$
\Phi(t_k, t_{k+1}) = \begin{bmatrix} I & | & \Delta tI \\ - & - & - \\ 0 & | & I \end{bmatrix} .
\tag{24}
$$

Thus, using the information from acceleration sensors, that are the part of inertia navigation system of the helicopter, you can significantly reduce the state vector with no loss of helicopter's hovering stabilization accuracy.

V. CONCLUSION

Using the information from the accelerations sensors, which are part of the inertial navigation system of the helicopter, you can significantly reduce the state vector $x(t_k)$ without perturbation of the requirements for accuracy of stabilization of helicopter's hovering over a point object. Besides, changes under the external influences of helicopter's accelerations $J(t_k)$ are characterized by short-period oscillations of the center of the helicopter's mass and significantly ahead in time changes in its velocity vector $V(t_k)$, which are characterized by long-period oscillations of the helicopter in space in relation to the given point O (Fig. 2) of the limited area object. The developed stabilizer (Fig.3), which is a part of ACS, solves the problem of simultaneous performance and storage stability of the automatic control system that is impossible to implement in standard schemes, where there is a contradiction, namely the growth of amplification coefficient, causes a decrease in supply stability of system of automatic stabilization and control.

REFERENCES

[1] V. Beltsov, Holdin the Sky In the Strong Hands. All-Russian aerospace journal "Herald of Aviation and Cosmonautics", no.1, 2000, pp. 8-10.

[2] W. Raymond Prouty and H. C. Curtiss, "Helicopter Control Systems: A History", Journal of Guidance, Control, and Dynamics, vol. 26, no. 1, 2003, pp. 12-18.

[3] R.W. Prouty, Helicopter Performance, Stability, and Control. first ed. Krieger Publishing Company, London, United Kingdom, 2002, p. 746.

[4] V.N. Kazak, A.A. Tunick, and V.I. Salimon, System of Automatic and Semi-automatic Flight Control. Monograph. Ed. by V.N. Kazak Kyiv, ed. NAU, 2002, p. 201.

[5] L. Livneh and G. Slater, Adaptive controller for wing flutter with unmeasurable excitations and unmodelled dynamics. "Int. J. Cont", 1991, 53, no. 2, pp. 293-309.

[6] V.M. Kazak, Fundamentals of control and technical diagnostics. K.: NAU, 2013, p. 300.

[7] V.M. Kazak, System recovery methods survivability of aircraft in special situations in flight: monograph. Kyiv, NAU, 2010, p. 284.

[8] Paul Verges, J.M. Sammons, S. Balakrishman, J.L. Speyer, and D.G. Hull, "Development and Comparison of Optimal Filters" AFATL – TR-79-87, Oct. 1979.

[9] T. Soderstrom, P. Stoica, and B. Friedlander, An indirect prediction error method for system identification. "Automatica", 1991, 27, no.1, pp. 183-188.

[10] E.S. Wentzel, Probability Theory: Proc. for universities. 6th ed. Moscow, Wysshaya shkola, 1999, p. 576.